

# THE THREAT TO LIFE FROM ETA CARINAE AND GAMMA-RAY BURSTS

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Eta Carinae, the most massive and luminous star known in our galaxy, is rapidly boiling matter off its surface. At any time its core could collapse into a black hole, which may result in a gamma-ray burst (GRB) that can devastate life on Earth. Auspiciously, recent observations indicate that the GRBs are narrowly beamed in cones along the rotational axis of the progenitor star. In the case of Eta Carinae the GRBs will not point to us, but will be ravaging to life on planets in our galaxy that happen to lie within the two beaming cones. The mean rate of massive life extinctions by jets from GRBs, per life-supporting planet in galaxies like ours, is once in 100 million years, comparable to the rate of major extinctions observed in the geological records of our planet.

Gamma ray bursts (GRBs) are short-duration flares of MeV  $\gamma$ -rays from outer space that last between a few milliseconds and  $\sim 1000$  s and occur at a rate of about 3 a day [1]. They were discovered serendipitously in 1967 by the Vela satellites launched by the US to monitor the compliance with the Nuclear Test Ban Treaty, banning nuclear explosions in and above the atmosphere. Their exact locations—and consequently their distance and total energy output—were unknown for 30 years, although their isotropy, established by observations with the BATSE instrument on board the Compton Gamma Ray Observatory satellite (CGRO) strongly suggested [2] cosmological distances [3]. Combined with the observed short-time variability of GRBs, such distances imply an enormous energy release from a small volume, if due to spherical explosions. Alternatively, it was argued that if GRB progenitors are so distant, they must be produced by narrow relativistic jets, from the birth of neutron stars or of black holes [4], [5].

The atmosphere is opaque to high energy  $\gamma$ -rays and cosmic ray nuclei, and protects life on Earth from their incoming constant flux. Collisions in the upper atmosphere, however, produce a flux of energetic muons that reach sea level, about  $10^{-2}$  muons  $s^{-1}$   $cm^{-2}$ . Life on Earth, apparently, has adjusted to the radiation damage from this small flux of atmospheric muons, each depositing through ionization, in biological materials, about  $2.4$  MeV  $g^{-1}$ . But, if very large fluxes of  $\gamma$ -rays and cosmic ray nuclei suddenly impinge on the atmosphere, they can have a devastating effect on life on Earth. In fact, it has been argued [6] that the highly beamed cosmic rays from GRBs in our galaxy, that happen to point in our direction, can produce lethal fluxes of atmospheric muons at ground level, underground and underwater, destroy the ozone layer and radioactivate the environment, so that GRBs could have caused some of the massive life extinctions on planet Earth in the past 500 My.

Before 1997 the above arguments were mere speculation. But supporting observational evidence accumulated after the significant discoveries of long-lasting GRB X-ray, optical and radio “afterglows”, made possible by the precise and prompt localization of GRBs by the Italian–Dutch satellite BeppoSAX [7]. The GRB and afterglow observations have shown beyond doubt that the “long” duration GRBs (which are the majority) take place in distant galaxies [8], mainly in star formation regions, and are associated with supernova explosions [9], [10]. Their large inferred energies, the properties of their afterglows, their apparent association with supernovae, and their global rate of  $\sim 1000$  per year, imply that GRBs are highly beamed [10], [11].

Because of the limited sizes of the satellite-borne detectors, GRBs have been observed mostly in the sub-MeV energy region, where the photon number flux, decreasing with increasing energy, is large enough. However, for a few very bright GRBs the EGRET instrument on board the CGRO detected  $\gamma$ -rays of up to GeV energies [12]. Moreover, four large ground-based  $\gamma$ -ray detectors, the Tibet air shower array, the HEGRA-AIROBICC Čerenkov array, the Milagro water-Čerenkov detector, and GRANDE, have reported possible detections of TeV  $\gamma$ -rays in directional and temporal coincidence with some GRBs detected by BATSE. In every case, the estimated total energy in TeV photons was about 2 orders of magnitude larger than the energy in sub-MeV photons measured by BATSE. In particular, GRANDE [13] and MILAGRITO [14] have reported the detection of unexpectedly large fluxes of muons coincident in time and direction with GRBs. These muons are allegedly produced by the interactions in the upper atmosphere

of  $\gamma$ -rays from the GRB with energies well above 100 GeV. These observations, if confirmed, would imply that GRBs are more lethal than they were previously thought to be. Since TeV photons are absorbed in the intergalactic infrared (IR) background by pair production, only relatively close-by GRBs (for which this absorption is insignificant) can be observed at TeV energies. This may explain why only a small fraction of the BATSE-detected GRBs in the fields of view of the various ground-based detectors were claimed to have been seen at TeV energies.

In Table I we list the measured redshift and fluence  $F_\gamma$  (in units of  $10^{-5}$  erg cm $^{-2}$ ) in the BATSE energy band, 40–2000 keV, for all GRBs with known redshift  $z$ . We also list their inferred luminosity distance  $D_L$  (in units of Gpc) and their total energy output,  $E_\gamma = 4\pi D_L^2 F_\gamma / (1+z)$  (in units of  $10^{53}$  erg), assuming isotropic emission and a critical Universe with a Hubble constant  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , fractional matter density  $\Omega_M = 0.3$  and vacuum energy density  $\Omega_\Lambda = 0.7$ .

Eta Carinae —a large blue variable star in the Carina constellation, more than 100 times as massive and 5 million times as luminous as the Sun— is one of the most massive and luminous stars known [15]. It is rapidly boiling matter off its surface. At any time its core could collapse into a black hole, which may result in a gamma-ray burst (GRB) [4], [5], [10]. Should the violent end of Eta Carinae, the most massive star known in our galaxy and only  $D = 2$  kpc away, emit in our direction a GRB similar to that of the most energetic GRB in Table I (GRB 990123), the atmosphere of Earth facing the star would be subject to a total energy deposition:

$$\frac{E_\gamma}{4\pi D_L^2} \approx 4 \times 10^9 \text{ erg cm}^{-2} \quad (1)$$

within seconds. This energy release is akin to that of the simultaneous explosions in the upper atmosphere of one-kiloton of TNT per km $^2$ , over the whole hemisphere facing Eta Carinae. This would destroy the ozone layer, create enormous shocks going down in the atmosphere, lit up huge fires and provoke giant global storms.

If the energy of GRBs in TeV  $\gamma$ -rays, as indicated by various experiments [13], [14], is  $\sim 100$  times larger than in the sub-MeV domain, the energy deposition of Eq. 1 would be correspondingly larger. Moreover, the interactions of the TeV  $\gamma$ -rays in the upper atmosphere would produce a lethal dose of highly penetrating muons, destroying life on the surface, underground and underwater. Indeed, a high energy  $\gamma$ -ray impinging on the atmosphere at a large zenith angle  $\theta$  produces  $\sim 0.23 \cos \theta [\epsilon_\gamma]^{1.17}$  muons at ground level [13], where  $\epsilon_\gamma$  is the  $\gamma$ -ray energy in TeV. Hence, the total muon fluence at ground level expected from a GRB from the supernova death of Eta Carinae is  $\sim 5 \times 10^{10} \text{ cm}^{-2}$  (the roughly linear dependence on the  $\gamma$ -ray energy makes this result sensitive only to the total deposited energy). The energy deposition by these high-energy muons in biological materials is  $\sim 2.5 \times 10^5 \text{ erg g}^{-1}$ , which is about ten times the lethal dose for human beings: the whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days [16].

All of the above, which would be devastating for life on Earth, would only happen if the  $\gamma$ -rays from Eta Carinae's supernova point in our direction. But would this GRB point to us? There are at least three known superheavy stars in our galaxy with a lifetime shorter than  $\sim 1$  My and expected to end in a giant supernova, implying that the galactic rate of giant supernovae is  $\geq 3 \times 10^{-6} \text{ y}^{-1}$ . The rate of massive life extinctions is  $\sim 10^{-8} \text{ y}^{-1}$ . Thus, if all galactic giant supernovae produced deadly GRBs, their  $\gamma$ -rays must be funnelled in a cone of opening angle  $\theta_b \leq 5^\circ$ , for two opposite GRBs per giant supernova. The chance probability for such cones to point in our direction is only  $3 \times 10^{-3}$ . But the expected direction for a jetted GRB is the progenitor's polar axis, which for Eta Carinae points  $57^\circ \pm 10^\circ$  away from our direction, judging from the radial velocities, proper motions and projected shape of its equatorial disk of debris [15]. This reduces considerably the chance that the GRBs from Eta Carinae point to our planet. Moreover, the properties of GRB afterglows and their association with Type Ib/Ic supernovae imply that GRBs are beamed into much narrower cones, of 1 mrad typical opening angle! [10]. This reduces to a negligible level the threat to terrestrial life from Eta Carinae.

Could Galactic GRBs beamed in our direction have caused some of the massive life extinctions in the history of Earth? The average energy output of a GRB is 5 times smaller than that of GRB 990123, as can be seen in Table I. The average distance of galactic GRBs from Earth, assuming they have the same spatial distribution as supernova remnants, is  $\sim 8$  kpc. Gamma rays alone from such “typical” GRBs can barely cause major mass extinctions, since

the frequency of such GRBs is too small to explain a mean rate of mass extinctions of once in  $\sim 100$  My, observed in the geological records [17]. However, if GRBs are produced in supernova explosions by highly relativistic jets of “cannonballs”, as suggested by the striking success of the Cannonball Model of GRBs in explaining their afterglows [10], the jetted cannonballs also produce highly beamed cosmic rays (CRs) by ionizing, sweeping up and accelerating the particles of the interstellar medium. Such CRs from galactic GRBs are much more devastating than their  $\gamma$ -rays. Let  $v$  be the speed of the CB and  $\Gamma \equiv 1/\sqrt{1-(v/c)^2} \gg 1$  be its Lorentz factor. The bulk of the swept up ISM particles entering the CB with energy  $\Gamma m c^2$  in its rest frame are deflected by the CB’s tangled magnetic fields, and are emitted isotropically in that frame. In the galactic rest frame their energy is Lorentz-boosted to an average energy  $m c^2 \Gamma^2$  and they are beamed into a cone of opening angle  $\theta \sim 1/\Gamma$ . Their energy distribution is related to the CBs’ deceleration by energy-momentum conservation, which yields  $dN_{\text{CR}}/d\Gamma \approx N_{\text{CB}}/\Gamma^2$ , where  $N_{\text{CB}}$  is the baryonic number of the CBs [10]. The afterglows of the GRBs listed in Table I are very well fitted with initial Lorentz factors  $\Gamma_i \simeq 10^3$  and total baryonic number  $N_{\text{jet}} \sim 6 \times 10^{50}$ , comparable to that of the Earth [10]. Thus, the energy fluence of CRs within their beaming cone of opening angle  $\theta \leq \Gamma_i$ , from a galactic GRB at a distance  $d \sim 8$  kpc, is:

$$F \simeq \frac{E_{\text{jet}} \Gamma_i^2}{3 \pi d^2} \simeq 1.5 \times 10^{12} \text{ erg cm}^{-2}. \quad (2)$$

Most of this fluence is spread over less than  $\Delta t \sim 2$  days, the typical CB deceleration time [10] from  $\Gamma = \Gamma_i$  to  $\Gamma = \Gamma_i/2$ . It is carried by CRs with energies between  $E = 2 m_p c^2 \Gamma_i^2 \sim 2 \times 10^3$  TeV and  $E = 0.4 m_p c^2 \Gamma_i^2/4 \sim 4 \times 10^2$  TeV<sup>1</sup>.

The ambient interstellar gas is transparent to the CR beam because the Coulomb and hadronic cross sections are rather small with respect to typical galactic column densities. Although the galactic magnetic field,  $B \sim 5 \times 10^{-6}$  Gauss, results in a Larmor radius  $r_L = \beta E_p/c q B \leq 10^{18}$  cm  $\ll 8$  kpc for single protons with  $E_p \leq 10^{15}$  eV, it does not deflect and disperse the CR beams from galactic GRBs. This is because of the high collimation of the CR beam which, even after travelling for a typical galactic distance —e.g.  $d \sim 8$  kpc, our distance from the Galaxy’s centre— has a very large energy and pressure within an angle  $\theta \leq 1/\Gamma_i$  from its direction of motion:  $E_{\text{CR}} \sim E_{\text{jet}}/3 \sim 3 \times 10^{51}$  erg and  $P_{\text{CR}} \sim E_{\text{jet}}/(3 \pi d^2 c \Delta t) \sim 3 \times 10^{-4}$  erg cm $^{-3}$ , respectively. These figures are much larger than the total magnetic energy of the swept-up galactic magnetic field inside the cone,  $d^3 B^2/24 \Gamma_i^2 \sim 1.5 \times 10^{49}$  erg and the galactic magnetic pressure  $B^2/8\pi \sim 10^{-12}$  erg cm $^{-3}$ . Thus, the CR beam sweeps away the magnetic field along its way and follows a straight ballistic trajectory through the interstellar medium. (The corresponding argument, when applied to the distant cosmological GRBs, lead to the opposite conclusion: no CRs from distant GRBs accompany the arrival of gamma rays.)

The beam of multi-TeV cosmic rays accompanying a galactic GRB is deadly for life on Earth-like planets. The total number of high energy muons ( $E_\mu \geq 25$  GeV) in the atmospheric showers produced by a cosmic ray proton with energy  $E_p \sim 10^2$  to  $10^3$  TeV is  $N_\mu(E > 25 \text{ GeV}) \sim 9.14 [E_p/\text{TeV}]^{0.757}/\cos\theta$  [18], yielding a muon fluence at ground level:

$$F_\mu(E > 25 \text{ GeV}) \simeq 1.7 \times 10^{12} \text{ cm}^{-2}. \quad (3)$$

Thus, the energy deposition rate at ground level in biological materials, due to exposure to atmospheric muons produced by an average GRB near the centre of the Galaxy, is  $4.2 \times 10^{12} \text{ MeV g}^{-1}$ . This is approximately 270 times the lethal dose for human beings. The lethal dosages for other vertebrates and insects can be a few times or as much as a factor 20 larger, respectively. Hence, CRs from galactic GRBs can produce a lethal dose of atmospheric muons for most animal species on Earth. Because of the large range of muons ( $\sim 4 [E_\mu/\text{GeV}] m$  in water), their flux is lethal, even hundreds of metres underwater and underground, for CRs arriving from well above the horizon. Thus, unlike other suggested extraterrestrial extinction mechanisms, the CRs of galactic GRBs can also explain massive extinctions deep underwater and underground. Although half of the planet is in the shade of the CR beam, its rotation exposes

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<sup>1</sup> The time delay of  $10^3$  TeV protons relative to photons over ballistic trajectories of 8 kpc is only  $8 \text{ kpc}/2 c \gamma^2 \simeq 0.41$  s.

a larger fraction of its surface to the CRs, whose arrival time is spread over  $\sim 2$  days. Additional effects increase the lethality of the CRs over the whole planet. They include:

- (a) Environmental pollution by radioactive nuclei, produced by spallation of atmospheric and surface nuclei by the secondary particles of the CR-induced showers.
- (b) Depletion of stratospheric ozone, which reacts with the nitric oxide generated by the CR-produced electrons (massive destruction of stratospheric ozone has been observed during large solar flares, which generate energetic protons).
- (c) Extensive damage to the food chain by radioactive pollution and massive extinction of vegetation by ionizing radiation (the lethal radiation dosages for trees and plants are slightly higher than those for animals, but still less than the flux given by Eq. 3 for all but the most resilient species).

Are the geological records of mass extinctions consistent with the effects induced by cosmic rays from GRBs? Good quality geological records, which extend up to  $\sim 500$  My ago, indicate that the exponential diversification of marine and continental life on Earth over that period was interrupted by many extinctions [17], with the major ones—exterminating more than 50% of the species on land and sea—occurring on average every 100 My. The five greatest events were those of the final Ordovician period (some 435 My ago), the late Devonian (357 My ago), the final Permian (251 My ago), the late Triassic (198 My ago) and the final Cretaceous (65 My ago). The observed rate of GRBs is  $\sim 10^3 \text{ y}^{-1}$ . The sky density of galaxies brighter than magnitude 25 (the observed mean magnitude of the host galaxies of the GRBs with known redshifts) in the Hubble telescope deep field is  $\sim 2 \times 10^5$  per square degree [19]. Thus, the rate of observed GRBs, per galaxy with luminosity similar to that of the Milky Way, is  $R \sim 1.2 \times 10^{-7} \text{ y}^{-1}$ . To translate this result into the number of GRBs born in our own galaxy, pointing to us, and occurring at (cosmologically) recent times, one must take into account that the GRB rate is proportional to the star formation rate, which increases with redshift like  $(1+z)^3$  [20]. For GRBs with known redshift (see Table I) one finds  $\langle 1+z \rangle \sim 2.1$ . In a flat Universe (like ours) the probability of a GRB to point to us within a certain angle is independent of distance. Therefore, the mean rate of GRBs pointing to us and taking place in our galaxy is roughly  $R/(1+z)^3 \sim 1.3 \times 10^{-8} \text{ y}^{-1}$ , or once every  $\sim 70$  My. If most of these GRBs take place not much farther away than the distance to the galactic centre, their effect is lethal, and their rate is consistent with the rate of the major mass extinctions on our planet in the past 500 My.

The geological records also indicate that two of the major mass extinctions were correlated in time with impacts of large meteorites or comets, with gigantic volcanic eruptions, with huge sea regressions and with drastic changes in global climate. A large meteoritic impact was invoked [21] in order to explain the iridium anomaly and the mass extinction that killed the dinosaurs and claimed 47% of existing genera at the Cretaceous-Tertiary (K/T) boundary, 65 My ago. Indeed, a 180 km wide crater was later discovered, buried under 1 km of Cenozoic sediments, dated back 65 My ago and apparently created by the impact of a  $\sim 10$  km diameter meteorite or comet near Chicxulub, in the Yucatan [22]. The huge Deccan basalt floods in India also occurred around the K/T boundary 65 My ago [23]. The Permian/Triassic (P/T) extinction, which killed between 80% and 95% of the species, is the largest known in the history of life [24]; it occurred 251 My ago, around the time of the gigantic Siberian basalt flood. Recently, possible evidence was found [25] for a large cometary impact at that time.

The orbits of comets indicate that they reside in a spherical cloud at the outer reaches of the solar system—the Oort Cloud [26]—with a typical radius of  $R_O \sim 50000$  AU. The statistics imply that it may contain as many as  $10^{12}$  comets with a total mass perhaps larger than that of Jupiter. The large value of  $R_O$  implies that the comets have very small binding energies and mean velocities of  $v \sim 100 \text{ m s}^{-1}$ . Small gravitational perturbations due to neighbouring stars are believed to disturb their orbits, unbind some of them, and put others into orbits that cross the inner solar system. The passage of the solar system through the spiral arms of the Galaxy where the density of stars is higher, could also have caused such perturbations and consequently the bombardment of Earth with a meteorite barrage of comets over an extended period longer than the free fall time from the Oort cloud to the Sun:

$$t_{\text{fall}} = \pi \left[ \frac{R_O^3}{8G M_\odot} \right]^{1/2} \simeq 1.7 \text{ My.} \quad (4)$$

The impact of comets and meteorites from the Oort cloud could have triggered the huge volcanic eruptions that

created the observed basalt floods, timed —within 1 to 2 My— around the K/T and P/T boundaries. Global climatic changes and sea regression followed, presumably from the injection of large quantities of light-blocking materials into the atmosphere, from the cometary impacts and the volcanic eruptions. In both the gigantic Deccan and Siberian basalt floods  $\sim 2 \times 10^6$  km<sup>3</sup> of lava were ejected. This is orders of magnitude larger than in any other known eruption, making it unlikely that the other major mass extinctions, which are of a similar magnitude, were produced by volcanic eruptions. The volcanic-quiet and impact-free extinctions could have been caused by GRBs. Moreover, passage of the GRB jet through the Oort cloud after sweeping up the interstellar matter on its way could also have generated perturbations, sending some comets into a collision course with Earth, perhaps explaining also the geologically active K/T and P/T extinctions.

The observation of planets orbiting nearby stars [27] has become almost routine, but current techniques are insufficient to detect planets with masses comparable to the Earth's. Future space-based observatories to detect Earth-like planets are being planned. Terrestrial planets orbiting in the habitable neighbourhood of stars, where planetary surface conditions are compatible with the presence of liquid water, might have global environments similar to ours, and harbour life. Our solar system is billions of years younger than most of the stars in the Milky Way. Life on extrasolar planets could have preceded life on Earth by billions of years, allowing for civilizations much more advanced than ours. Thus Fermi's famous question “where are they?”, i.e. why did they not visit us or send signals to us? An answer is provided by GRB-induced mass extinctions: even if advanced civilizations are not self-destructive, GRBs can exterminate the most evolved species on any given planet or interstellar vehicle at a mean rate of once every 100 My. Consequently, there may be no nearby aliens having evolved long enough to be capable of communicating with us, or pay us a visit.

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**Table I - GRBs of known redshift**

GRB	z	D <sub>L</sub>	F <sub>γ</sub>	E <sub>γ</sub>
970228	0.695	4.55	1.1	0.22
970508	0.835	5.70	0.32	0.07
970828	0.957	6.74	9.6	2.06
971214	3.418	32.0	0.94	2.11
980425	.0085	.039	0.44	8.1E-6
980613	1.096	7.98	0.17	0.61
980703	0.966	6.82	2.26	1.05
990123	1.600	12.7	26.8	19.80
990510	1.619	12.9	6.55	5.00
990712	0.434	2.55	6.5	0.53
991208	0.70	4.64	10.0	1.51
991216	1.020	7.30	19.4	5.35
000131	4.500	44.4	4.2	11.60
000301c	2.040	17.2	0.41	0.46
000418	1.119	8.18	2.0	0.82
000911	1.06	7.66	2.0	0.68
000926	2.066	17.4	2.20	10.54
010222	1.474	11.5	12.0	7.80

Redshift z. Luminosity distance, D<sub>L</sub>, in Gpc. Fluence measured by BATSE, F<sub>γ</sub>, in 10<sup>-5</sup> erg cm<sup>-2</sup> units. Deduced spherical energy, E<sub>γ</sub>, in 10<sup>53</sup> erg units.

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Gamma ray bursts (GRBs) are short-duration flares of MeV  $\gamma$ -rays from outer space that last between a few milliseconds and  $\sim 1000$  s and occur at a rate of about 3 a day [1]. They were discovered serendipitously in 1967 by the Vela satellites launched by the US to monitor the compliance with the Nuclear Test Ban Treaty, banning nuclear explosions in and above the atmosphere. Their exact locations—and consequently their distance and total energy output—were unknown for 30 years, although their isotropy, established by observations with the BATSE instrument on board the Compton Gamma Ray Observatory satellite (CGRO) strongly suggested [2] cosmological distances [3]. Combined with the observed short-time variability of GRBs, such distances imply an enormous energy release from a small volume, if due to spherical explosions. Alternatively, it was argued that if GRB progenitors are so distant, they must be produced by narrow relativistic jets, from the birth of neutron stars or of black holes [4], [5].

The atmosphere is opaque to high energy  $\gamma$ -rays and cosmic ray nuclei, and protects life on Earth from their incoming constant flux. Collisions in the upper atmosphere, however, produce a flux of energetic muons that reach sea level, about  $10^{-2}$  muons  $s^{-1}$   $cm^{-2}$ . Life on Earth, apparently, has adjusted to the radiation damage from this small flux of atmospheric muons, each depositing through ionization, in biological materials, about  $2.4$  MeV  $g^{-1}$ . But, if very large fluxes of  $\gamma$ -rays and cosmic ray nuclei suddenly impinge on the atmosphere, they can have a devastating effect on life on Earth. In fact, it has been argued [6] that the highly beamed cosmic rays from GRBs in our galaxy, that happen to point in our direction, can produce lethal fluxes of atmospheric muons at ground level, underground and underwater, destroy the ozone layer and radioactivate the environment, so that GRBs could have caused some of the massive life extinctions on planet Earth in the past 500 My.

Before 1997 the above arguments were mere speculation. But supporting observational evidence accumulated after the significant discoveries of long-lasting GRB X-ray, optical and radio “afterglows”, made possible by the precise and prompt localization of GRBs by the Italian–Dutch satellite BeppoSAX [7]. The GRB and afterglow observations have shown beyond doubt that the “long” duration GRBs (which are the majority) take place in distant galaxies [8], mainly in star formation regions, and are associated with supernova explosions [9], [10]. Their large inferred energies, the properties of their afterglows, their apparent association with supernovae, and their global rate of  $\sim 1000$  per year, imply that GRBs are highly beamed [10], [11].

Because of the limited sizes of the satellite-borne detectors, GRBs have been observed mostly in the sub-MeV energy region, where the photon number flux, decreasing with increasing energy, is large enough. However, for a few very bright GRBs the EGRET instrument on board the CGRO detected  $\gamma$ -rays of up to GeV energies [12]. Moreover, four large ground-based  $\gamma$ -ray detectors, the Tibet air shower array, the HEGRA-AIROBICC Čerenkov array, the Milagro water-Čerenkov detector, and GRANDE, have reported possible detections of TeV  $\gamma$ -rays in directional and temporal coincidence with some GRBs detected by BATSE. In every case, the estimated total energy in TeV photons was about 2 orders of magnitude larger than the energy in sub-MeV photons measured by BATSE. In particular, GRANDE [13] and MILAGRITO [14] have reported the detection of unexpectedly large fluxes of muons coincident in time and direction with GRBs. These muons are allegedly produced by the interactions in the upper atmosphere

of  $\gamma$ -rays from the GRB with energies well above 100 GeV. These observations, if confirmed, would imply that GRBs are more lethal than they were previously thought to be. Since TeV photons are absorbed in the intergalactic infrared (IR) background by pair production, only relatively close-by GRBs (for which this absorption is insignificant) can be observed at TeV energies. This may explain why only a small fraction of the BATSE-detected GRBs in the fields of view of the various ground-based detectors were claimed to have been seen at TeV energies.

In Table I we list the measured redshift and fluence  $F_\gamma$  (in units of  $10^{-5}$  erg cm $^{-2}$ ) in the BATSE energy band, 40–2000 keV, for all GRBs with known redshift  $z$ . We also list their inferred luminosity distance  $D_L$  (in units of Gpc) and their total energy output,  $E_\gamma = 4\pi D_L^2 F_\gamma / (1+z)$  (in units of  $10^{53}$  erg), assuming isotropic emission and a critical Universe with a Hubble constant  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , fractional matter density  $\Omega_M = 0.3$  and vacuum energy density  $\Omega_\Lambda = 0.7$ .

Eta Carinae —a large blue variable star in the Carina constellation, more than 100 times as massive and 5 million times as luminous as the Sun— is one of the most massive and luminous stars known [15]. It is rapidly boiling matter off its surface. At any time its core could collapse into a black hole, which may result in a gamma-ray burst (GRB) [4], [5], [10]. Should the violent end of Eta Carinae, the most massive star known in our galaxy and only  $D = 2$  kpc away, emit in our direction a GRB similar to that of the most energetic GRB in Table I (GRB 990123), the atmosphere of Earth facing the star would be subject to a total energy deposition:

$$\frac{E_\gamma}{4\pi D_L^2} \approx 4 \times 10^9 \text{ erg cm}^{-2} \quad (1)$$

within seconds. This energy release is akin to that of the simultaneous explosions in the upper atmosphere of one-kiloton of TNT per km $^2$ , over the whole hemisphere facing Eta Carinae. This would destroy the ozone layer, create enormous shocks going down in the atmosphere, lit up huge fires and provoke giant global storms.

If the energy of GRBs in TeV  $\gamma$ -rays, as indicated by various experiments [13], [14], is  $\sim 100$  times larger than in the sub-MeV domain, the energy deposition of Eq. 1 would be correspondingly larger. Moreover, the interactions of the TeV  $\gamma$ -rays in the upper atmosphere would produce a lethal dose of highly penetrating muons, destroying life on the surface, underground and underwater. Indeed, a high energy  $\gamma$ -ray impinging on the atmosphere at a large zenith angle  $\theta$  produces  $\sim 0.23 \cos \theta [\epsilon_\gamma]^{1.17}$  muons at ground level [13], where  $\epsilon_\gamma$  is the  $\gamma$ -ray energy in TeV. Hence, the total muon fluence at ground level expected from a GRB from the supernova death of Eta Carinae is  $\sim 5 \times 10^{10} \text{ cm}^{-2}$  (the roughly linear dependence on the  $\gamma$ -ray energy makes this result sensitive only to the total deposited energy). The energy deposition by these high-energy muons in biological materials is  $\sim 2.5 \times 10^5 \text{ erg g}^{-1}$ , which is about ten times the lethal dose for human beings: the whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days [16].

All of the above, which would be devastating for life on Earth, would only happen if the  $\gamma$ -rays from Eta Carinae's supernova point in our direction. But would this GRB point to us? There are at least three known superheavy stars in our galaxy with a lifetime shorter than  $\sim 1$  My and expected to end in a giant supernova, implying that the galactic rate of giant supernovae is  $\geq 3 \times 10^{-6} \text{ y}^{-1}$ . The rate of massive life extinctions is  $\sim 10^{-8} \text{ y}^{-1}$ . Thus, if all galactic giant supernovae produced deadly GRBs, their  $\gamma$ -rays must be funnelled in a cone of opening angle  $\theta_b \leq 5^\circ$ , for two opposite GRBs per giant supernova. The chance probability for such cones to point in our direction is only  $3 \times 10^{-3}$ . But the expected direction for a jetted GRB is the progenitor's polar axis, which for Eta Carinae points  $57^\circ \pm 10^\circ$  away from our direction, judging from the radial velocities, proper motions and projected shape of its equatorial disk of debris [15]. This reduces considerably the chance that the GRBs from Eta Carinae point to our planet. Moreover, the properties of GRB afterglows and their association with Type Ib/Ic supernovae imply that GRBs are beamed into much narrower cones, of 1 mrad typical opening angle! [10]. This reduces to a negligible level the threat to terrestrial life from Eta Carinae.

Could Galactic GRBs beamed in our direction have caused some of the massive life extinctions in the history of Earth? The average energy output of a GRB is 5 times smaller than that of GRB 990123, as can be seen in Table I. The average distance of galactic GRBs from Earth, assuming they have the same spatial distribution as supernova remnants, is  $\sim 8$  kpc. Gamma rays alone from such “typical” GRBs can barely cause major mass extinctions, since

the frequency of such GRBs is too small to explain a mean rate of mass extinctions of once in  $\sim 100$  My, observed in the geological records [17]. However, if GRBs are produced in supernova explosions by highly relativistic jets of “cannonballs”, as suggested by the striking success of the Cannonball Model of GRBs in explaining their afterglows [10], the jetted cannonballs also produce highly beamed cosmic rays (CRs) by ionizing, sweeping up and accelerating the particles of the interstellar medium. Such CRs from galactic GRBs are much more devastating than their  $\gamma$ -rays. Let  $v$  be the speed of the CB and  $\Gamma \equiv 1/\sqrt{1-(v/c)^2} \gg 1$  be its Lorentz factor. The bulk of the swept up ISM particles entering the CB with energy  $\Gamma m c^2$  in its rest frame are deflected by the CB’s tangled magnetic fields, and are emitted isotropically in that frame. In the galactic rest frame their energy is Lorentz-boosted to an average energy  $m c^2 \Gamma^2$  and they are beamed into a cone of opening angle  $\theta \sim 1/\Gamma$ . Their energy distribution is related to the CBs’ deceleration by energy-momentum conservation, which yields  $dN_{\text{CR}}/d\Gamma \approx N_{\text{CB}}/\Gamma^2$ , where  $N_{\text{CB}}$  is the baryonic number of the CBs [10]. The afterglows of the GRBs listed in Table I are very well fitted with initial Lorentz factors  $\Gamma_i \simeq 10^3$  and total baryonic number  $N_{\text{jet}} \sim 6 \times 10^{50}$ , comparable to that of the Earth [10]. Thus, the energy fluence of CRs within their beaming cone of opening angle  $\theta \leq \Gamma_i$ , from a galactic GRB at a distance  $d \sim 8$  kpc, is:

$$F \simeq \frac{E_{\text{jet}} \Gamma_i^2}{3 \pi d^2} \simeq 1.5 \times 10^{12} \text{ erg cm}^{-2}. \quad (2)$$

Most of this fluence is spread over less than  $\Delta t \sim 2$  days, the typical CB deceleration time [10] from  $\Gamma = \Gamma_i$  to  $\Gamma = \Gamma_i/2$ . It is carried by CRs with energies between  $E = 2 m_p c^2 \Gamma_i^2 \sim 2 \times 10^3$  TeV and  $E = 0.4 m_p c^2 \Gamma_i^2/4 \sim 4 \times 10^2$  TeV<sup>1</sup>.

The ambient interstellar gas is transparent to the CR beam because the Coulomb and hadronic cross sections are rather small with respect to typical galactic column densities. Although the galactic magnetic field,  $B \sim 5 \times 10^{-6}$  Gauss, results in a Larmor radius  $r_L = \beta E_p/c q B \leq 10^{18}$  cm  $\ll 8$  kpc for single protons with  $E_p \leq 10^{15}$  eV, it does not deflect and disperse the CR beams from galactic GRBs. This is because of the high collimation of the CR beam which, even after travelling for a typical galactic distance —e.g.  $d \sim 8$  kpc, our distance from the Galaxy’s centre— has a very large energy and pressure within an angle  $\theta \leq 1/\Gamma_i$  from its direction of motion:  $E_{\text{CR}} \sim E_{\text{jet}}/3 \sim 3 \times 10^{51}$  erg and  $P_{\text{CR}} \sim E_{\text{jet}}/(3 \pi d^2 c \Delta t) \sim 3 \times 10^{-4}$  erg cm $^{-3}$ , respectively. These figures are much larger than the total magnetic energy of the swept-up galactic magnetic field inside the cone,  $d^3 B^2/24 \Gamma_i^2 \sim 1.5 \times 10^{49}$  erg and the galactic magnetic pressure  $B^2/8\pi \sim 10^{-12}$  erg cm $^{-3}$ . Thus, the CR beam sweeps away the magnetic field along its way and follows a straight ballistic trajectory through the interstellar medium. (The corresponding argument, when applied to the distant cosmological GRBs, lead to the opposite conclusion: no CRs from distant GRBs accompany the arrival of gamma rays.)

The beam of multi-TeV cosmic rays accompanying a galactic GRB is deadly for life on Earth-like planets. The total number of high energy muons ( $E_\mu \geq 25$  GeV) in the atmospheric showers produced by a cosmic ray proton with energy  $E_p \sim 10^2$  to  $10^3$  TeV is  $N_\mu(E > 25 \text{ GeV}) \sim 9.14 [E_p/\text{TeV}]^{0.757}/\cos\theta$  [18], yielding a muon fluence at ground level:

$$F_\mu(E > 25 \text{ GeV}) \simeq 1.7 \times 10^{12} \text{ cm}^{-2}. \quad (3)$$

Thus, the energy deposition rate at ground level in biological materials, due to exposure to atmospheric muons produced by an average GRB near the centre of the Galaxy, is  $4.2 \times 10^{12} \text{ MeV g}^{-1}$ . This is approximately 270 times the lethal dose for human beings. The lethal dosages for other vertebrates and insects can be a few times or as much as a factor 20 larger, respectively. Hence, CRs from galactic GRBs can produce a lethal dose of atmospheric muons for most animal species on Earth. Because of the large range of muons ( $\sim 4 [E_\mu/\text{GeV}] m$  in water), their flux is lethal, even hundreds of metres underwater and underground, for CRs arriving from well above the horizon. Thus, unlike other suggested extraterrestrial extinction mechanisms, the CRs of galactic GRBs can also explain massive extinctions deep underwater and underground. Although half of the planet is in the shade of the CR beam, its rotation exposes

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<sup>1</sup> The time delay of  $10^3$  TeV protons relative to photons over ballistic trajectories of 8 kpc is only  $8 \text{ kpc}/2 c \gamma^2 \simeq 0.41$  s.

a larger fraction of its surface to the CRs, whose arrival time is spread over  $\sim 2$  days. Additional effects increase the lethality of the CRs over the whole planet. They include:

- (a) Environmental pollution by radioactive nuclei, produced by spallation of atmospheric and surface nuclei by the secondary particles of the CR-induced showers.
- (b) Depletion of stratospheric ozone, which reacts with the nitric oxide generated by the CR-produced electrons (massive destruction of stratospheric ozone has been observed during large solar flares, which generate energetic protons).
- (c) Extensive damage to the food chain by radioactive pollution and massive extinction of vegetation by ionizing radiation (the lethal radiation dosages for trees and plants are slightly higher than those for animals, but still less than the flux given by Eq. 3 for all but the most resilient species).

Are the geological records of mass extinctions consistent with the effects induced by cosmic rays from GRBs? Good quality geological records, which extend up to  $\sim 500$  My ago, indicate that the exponential diversification of marine and continental life on Earth over that period was interrupted by many extinctions [17], with the major ones—exterminating more than 50% of the species on land and sea—occurring on average every 100 My. The five greatest events were those of the final Ordovician period (some 435 My ago), the late Devonian (357 My ago), the final Permian (251 My ago), the late Triassic (198 My ago) and the final Cretaceous (65 My ago). The observed rate of GRBs is  $\sim 10^3 \text{ y}^{-1}$ . The sky density of galaxies brighter than magnitude 25 (the observed mean magnitude of the host galaxies of the GRBs with known redshifts) in the Hubble telescope deep field is  $\sim 2 \times 10^5$  per square degree [19]. Thus, the rate of observed GRBs, per galaxy with luminosity similar to that of the Milky Way, is  $R \sim 1.2 \times 10^{-7} \text{ y}^{-1}$ . To translate this result into the number of GRBs born in our own galaxy, pointing to us, and occurring at (cosmologically) recent times, one must take into account that the GRB rate is proportional to the star formation rate, which increases with redshift like  $(1+z)^3$  [20]. For GRBs with known redshift (see Table I) one finds  $\langle 1+z \rangle \sim 2.1$ . In a flat Universe (like ours) the probability of a GRB to point to us within a certain angle is independent of distance. Therefore, the mean rate of GRBs pointing to us and taking place in our galaxy is roughly  $R/(1+z)^3 \sim 1.3 \times 10^{-8} \text{ y}^{-1}$ , or once every  $\sim 70$  My. If most of these GRBs take place not much farther away than the distance to the galactic centre, their effect is lethal, and their rate is consistent with the rate of the major mass extinctions on our planet in the past 500 My.

The geological records also indicate that two of the major mass extinctions were correlated in time with impacts of large meteorites or comets, with gigantic volcanic eruptions, with huge sea regressions and with drastic changes in global climate. A large meteoritic impact was invoked [21] in order to explain the iridium anomaly and the mass extinction that killed the dinosaurs and claimed 47% of existing genera at the Cretaceous-Tertiary (K/T) boundary, 65 My ago. Indeed, a 180 km wide crater was later discovered, buried under 1 km of Cenozoic sediments, dated back 65 My ago and apparently created by the impact of a  $\sim 10$  km diameter meteorite or comet near Chicxulub, in the Yucatan [22]. The huge Deccan basalt floods in India also occurred around the K/T boundary 65 My ago [23]. The Permian/Triassic (P/T) extinction, which killed between 80% and 95% of the species, is the largest known in the history of life [24]; it occurred 251 My ago, around the time of the gigantic Siberian basalt flood. Recently, possible evidence was found [25] for a large cometary impact at that time.

The orbits of comets indicate that they reside in a spherical cloud at the outer reaches of the solar system—the Oort Cloud [26]—with a typical radius of  $R_O \sim 50000$  AU. The statistics imply that it may contain as many as  $10^{12}$  comets with a total mass perhaps larger than that of Jupiter. The large value of  $R_O$  implies that the comets have very small binding energies and mean velocities of  $v \sim 100 \text{ m s}^{-1}$ . Small gravitational perturbations due to neighbouring stars are believed to disturb their orbits, unbind some of them, and put others into orbits that cross the inner solar system. The passage of the solar system through the spiral arms of the Galaxy where the density of stars is higher, could also have caused such perturbations and consequently the bombardment of Earth with a meteorite barrage of comets over an extended period longer than the free fall time from the Oort cloud to the Sun:

$$t_{\text{fall}} = \pi \left[ \frac{R_O^3}{8G M_\odot} \right]^{1/2} \simeq 1.7 \text{ My.} \quad (4)$$

The impact of comets and meteorites from the Oort cloud could have triggered the huge volcanic eruptions that

created the observed basalt floods, timed —within 1 to 2 My— around the K/T and P/T boundaries. Global climatic changes and sea regression followed, presumably from the injection of large quantities of light-blocking materials into the atmosphere, from the cometary impacts and the volcanic eruptions. In both the gigantic Deccan and Siberian basalt floods  $\sim 2 \times 10^6$  km<sup>3</sup> of lava were ejected. This is orders of magnitude larger than in any other known eruption, making it unlikely that the other major mass extinctions, which are of a similar magnitude, were produced by volcanic eruptions. The volcanic-quiet and impact-free extinctions could have been caused by GRBs. Moreover, passage of the GRB jet through the Oort cloud after sweeping up the interstellar matter on its way could also have generated perturbations, sending some comets into a collision course with Earth, perhaps explaining also the geologically active K/T and P/T extinctions.

The observation of planets orbiting nearby stars [27] has become almost routine, but current techniques are insufficient to detect planets with masses comparable to the Earth's. Future space-based observatories to detect Earth-like planets are being planned. Terrestrial planets orbiting in the habitable neighbourhood of stars, where planetary surface conditions are compatible with the presence of liquid water, might have global environments similar to ours, and harbour life. Our solar system is billions of years younger than most of the stars in the Milky Way. Life on extrasolar planets could have preceded life on Earth by billions of years, allowing for civilizations much more advanced than ours. Thus Fermi's famous question “where are they?”, i.e. why did they not visit us or send signals to us? An answer is provided by GRB-induced mass extinctions: even if advanced civilizations are not self-destructive, GRBs can exterminate the most evolved species on any given planet or interstellar vehicle at a mean rate of once every 100 My. Consequently, there may be no nearby aliens having evolved long enough to be capable of communicating with us, or pay us a visit.

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**Table I - GRBs of known redshift**

GRB	z	D <sub>L</sub>	F <sub>γ</sub>	E <sub>γ</sub>
970228	0.695	4.55	1.1	0.22
970508	0.835	5.70	0.32	0.07
970828	0.957	6.74	9.6	2.06
971214	3.418	32.0	0.94	2.11
980425	.0085	.039	0.44	8.1E-6
980613	1.096	7.98	0.17	0.61
980703	0.966	6.82	2.26	1.05
990123	1.600	12.7	26.8	19.80
990510	1.619	12.9	6.55	5.00
990712	0.434	2.55	6.5	0.53
991208	0.70	4.64	10.0	1.51
991216	1.020	7.30	19.4	5.35
000131	4.500	44.4	4.2	11.60
000301c	2.040	17.2	0.41	0.46
000418	1.119	8.18	2.0	0.82
000911	1.06	7.66	2.0	0.68
000926	2.066	17.4	2.20	10.54
010222	1.474	11.5	12.0	7.80

Redshift z. Luminosity distance, D<sub>L</sub>, in Gpc. Fluence measured by BATSE, F<sub>γ</sub>, in 10<sup>-5</sup> erg cm<sup>-2</sup> units. Deduced spherical energy, E<sub>γ</sub>, in 10<sup>53</sup> erg units.